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IS THE CCC A NEW DEAL FOR BARYON SPECTROSCOPY?*

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ABSTRACT

The possibility of experimental observation of the triply charmed ccc baryon Ω_{ccc}^{++} is explored. The conclusion is that it is very difficult, but not unthinkable.

INTRODUCTION

In the decade since the discovery of the ψ, a great deal has been learned about mesons containing the heavy quarks c and b. The future promises to hold even more - both in e^+e^- collisions and in hadron collisions.

The issue of heavy-quark hadron studies via incident hadron beams is one of special interest to me these days.[1,2] There are in principle great opportunities for high-statistics studies. Nevertheless, the fierce background problems pose a formidable barrier. It is therefore a serious question whether it is worth the heavy effort to try to outdo the capabilities of the e^+e^- experiments, which give exquisitely clean D and B samples at threshold and which provide good signal-to-noise at all energies. And SLC/LEP will improve the statistics of high-energy samples ten to hundred-fold when they turn on.

One answer to this challenge is to emphasize complementarity. While the e^+e^- process is good for D, D*, B, and B*, it as yet is much less powerful for F, B_s, and baryons. Baryons in particular seem to be copiously produced in hadron-induced fixed target experiments, as evidenced by observation[3] of A^+(cus) and T^0(ssc). Therefore a reasonable strategy for fixed target experiments may be to continue the pursuit of states containing as large a number possible of s, c, and b quarks, and especially baryons.

From the theoretical point of view there are reasons for doing this as well. Historically, baryon spectroscopy provided rich, clean evidence for the quark model when it was needed: I am thinking of the phase-shift analyses of the early 1970's which by November 1974 could be succinctly summarized[4] as "$\underline{56}$, L even plus $\underline{70}$, L odd." And the more recent QCD analyses have likewise been impressively successful.

Looking toward the future, we may expect that interest in the question of how baryons are put together from quarks will not diminish. One need go no further than the large uncertainty in estimates of proton-decay due to unknown wave-functions to appreciate that. A new dimension for the future would be the understanding of baryons containing only heavy quarks; the mesonic analogue after all has been of crucial significance. Just as anticipated observations of the $t\bar{t}$ mesons are especially interesting to the QCD theorist, so also would be the observations of the properties of ttt baryons. That would appear to be out of the question experimentally for the foreseeable future. But already the ssc system (observed!) begins to enter the purely heavy quark world-in the same sense that it is not totally foolish to regard the ϕ as "strange-onium". Why not search for the ccs, or bcs?

It is our purpose here to discuss what might be possible. We shall do this not by trying to make a general survey (that is a big job) but, just for fun, to concentrate on the single case of the triply charmed $(ccc)^{++}$ baryon. It has that esthetic quality possessed by the Ω^- and would be wonderful to observe. It may be beyond the fringe to take that possibility seriously. But better to try to reach too far than not far enough. And by studying the prospects for (ccc) we learn something about what is between us and it. That is interesting too.

In the subsequent sections, we lay out a search program. We begin with mass estimates, then decay schemes, and then production cross-section guesses. We then determine the experimental requirements and lay out possible experimental attacks. In the final section we try to come to our senses and infer some conclusions.

MASS FORMULAE

There is not too much uncertainty in the expectations for the (ccc) mass. We here take a simple-minded approach, and assume (ignoring QCD logarithms)

$$\frac{m(QQQ)}{m(Q\bar{Q})} \cong \frac{3}{2} + \frac{\text{constant}}{m^{4/3}} + \frac{\text{constant}}{\ln^2 m/m_0} \qquad (1)$$

The correction terms are contributed by binding contributions from a linear plus coulomb two-body potential. Inasmuch as

$$\frac{\Delta}{\rho} = 1.60 \qquad \frac{\Delta}{\omega} = 1.58 \qquad \frac{\Omega}{\phi} = 1.64 \qquad (2)$$

a reasonable estimate for the heavier baryons is

$$\frac{ccc}{\psi} = 1.59 \pm .03 \qquad \frac{bbb}{\Upsilon} = 1.56 \pm .02 \tag{3}$$

We next assume validity of the "equal-spacing" rule for the masses of all the J = 3/2 baryons which interpolate between ccc, bbb, and ordinary baryons. This gives rise to the values given in Table I. The asterisks are to remind one that that particular state is unstable, decaying to a J = 1/2 ground state, usually via an M1 photon.

Table I

Estimated Masses of J=3/2 Baryons (MeV)

(ccc)	4925 ± 90
(ccs)*	3840 ± 60
(css)*	2755 ± 30
(ccu)*	3695 ± 60
(csu)*	2608 ± 30
(cuu)*	2463 ± 30

(bbb)	14,760 ± 180	(bbc)*	11,480 ± 120
(bbs)*	10,395 ± 120	(bcc)*	8,200 ± 90
(bss)*	6,035 ± 60	(bcs)*	7,120 ± 70
(bbu)*	10,250 ± 120	(bcu)*	5,970 ± 70
(bsu)*	5,890 ± 60		
(buu)*	5,740 ± 60		

Table II

Estimated Masses of J = 1/2 Baryons (MeV). We omit errors; these are estimated relative to the central J = 3/2 values.

(ccs)	3800
(css)	2715
(ccu)	3635
(csu)*	2558
(csu)	2468
(cuu)*	2403
(cud)	2243

We see that, in addition to the familiar rule that replacement of u → s costs 145 MeV (in the J = 3/2 multiplet), we have the rules $s \to c$ costs 1085 ± 30 GeV, and $c \to b$ costs ~ 3280 GeV. These "Q-values" are considerably smaller than their mesonic counterparts.

To obtain the $J = 1/2$ mass values, we may use the analyses of hyperfine splittings as pioneered[5] by DeRujula, Georgi, and Glashow. We here take the values quoted by them and thereby them obtain the collection shown in Table II.

DECAY PROPERTIES

There seems to be no other mechanism for $(ccc)^{++}$ decay than the "spectator" mechanism. Hence a reasonable estimate for (ccc) lifetime is obtained by normalizing it to the D^+ lifetime, which is in turn a pretty good candidate for the spectator model. Thus the naive estimate would be

$$\tau_{ccc} \cong \frac{1}{3} \tau_{D^+} \cong 3 \times 10^{-13} \text{ sec.} \tag{4}$$

As already mentioned, the phase-space corrections may be quite relevant; they probably tend to increase the ccc lifetime. However, in order to estimate that better, one needs to understand the decay mechanisms. Several candidates exist:

1) <u>Factorization</u>

By this we mean

$$(ccc) \to (ccs) + \pi^+, \rho^+, \ldots \tag{5}$$

This seems a good candidate mechanism, given the success[6] of the corresponding "factorization" mechanism in describing the major portion of D and B decays. Nevertheless, the apparently large branching ratios for

$$A(cus) \to \Lambda K^- \pi^+ \pi^+ \tag{6}$$

$$T(ssc) \to \Xi K^- \pi^+ \pi^+ \tag{7}$$

and perhaps[7] even

$$\Lambda_c \text{ (cud)} \to pK_S \pi^+ \pi^- \tag{8}$$

do not seem to easily fit into that picture.

2) Rearrangement

Here we mean

$$(ccc) \to (ccq) + K,\ K^* \tag{9}$$

where q stands for u or d. This pattern occurs because of Fierz rearrangement of the four-fermi interaction. This is suppressed in the case of meson decays. It may be different in baryon decays because the initial-state color structure is different.

3) Four-body

This is again

$$ccc \to (ccq) + K\ \pi\pi \tag{10}$$

However, what is envisaged is that each decay-product quark flying away from the residual spectator diquark produces a string (to the diquark) which breaks. Hence the diquark picks up a nonstrange quark. The three outgoing mesons need not resonate.

4) Diquark breakup

In this case,

$$\begin{aligned}(ccc) &\to (cqq) + (c\bar{q}) + (s\bar{q}) + \pi\text{'s} \\ &= \Lambda_c + D^+ + K^- + \pi\text{'s}\end{aligned} \tag{11}$$

Alternatively,

$$(ccc) \to A + D + \pi\text{'s} \tag{12}$$

These channels are kinematically allowed. But it seems to this author that the diquark has no reason to break up with high probability; hence these modes ought to be rather rare.

Based on these mechanisms, crude guesses as to decay modes and branching fractions for (ccc) are given in Table III. We see that, irrespective of the question of which mechanism dominates (other than the diquark breakup), the baryon remaining is doubly charmed, ccq or ccs. This residual baryon should then cascade down, via essentially the same mix of mechanisms to a singly charmed baryon. Thus, it is very reasonable that more than 50% of the final states go into A and/or T, channels for which there do exist successful signatures!!

Table III

Some guesses for decay modes and branching fractions of the (ccc). (Radiative photons from $B^* \to B$ are disregarded here).

Final State	Available Kinetic Energy (MeV)	Branching Ratio
(ccs) $e\nu$	1080	15-20%
(ccs) $\mu\nu$	980	15-20%
		35±5%
(ccs) π^+	930	8-15%
(ccs) $\pi^+\pi^0$	790	12-20%
(ccs) $\pi^+\pi^+\pi^-$	650	5-10%
		35±10%
(ccu) K^0	765	2-6%
(ccu) K^{0*}	380	4-12%
(ccd) K^+	765	1-3%
(ccd) K^{+*}	380	3-9%
		20±10%
(cus) $D(n\pi)$	525-140n	7 ± 4% ?
(cud) DK	250	3 ± 2 ?

The second cascade ccs → cqs + ..., etc. should be characterized by a longer lifetime, i.e.,

$$\tau_{(ccs)} \sim \tau_{(ccq)} \sim \frac{1}{2}\tau_{D^+} \tag{13}$$

just as one expects

$$\tau_A \approx \tau_T \approx \tau_{D^+} \tag{14}$$

This is evidently consistent with the known lifetime information.

We should also mention that the intermediate baryons may be excited, either in the J = 3/2 state or, in the case of csu, into the J = 1/2 partner of the T, which has a different internal symmetry for its wave function (the analog of Σ^0 to Λ). In these cases the de-excitation is radiative, with a γ-ray in the 60 ± 30 MeV range (in the baryon rest frame). These cascade γ's may provide an additional tag that the event is interesting.

Finally, we must mention semileptonic decays. The process

$$(ccc) \rightarrow (ccs)\ \ell\nu \qquad (15)$$

probably is dominated (because of phase-space and a big Gamow-Teller matrix element) by the $J = 3/2 \rightarrow J = 1/2$ transition to the ccs ground state. What happens in the next step is less clear without a calculation: does the Fermi transition dominate, or is there excitation of the $J = 3/2$ $(ccs)^* \rightarrow T \pm \Upsilon$? In either case, however, one is left with the T. It in turn can decay semileptonically to Ω^-. All three cascades, in the spectator model, should have the same semileptonic branching ratio as $D^{\pm}{}_{0}$ namely ~ 17%.

For the devotee of leptonic (probably muonic) triggers, this cascade scheme has the net effect

$$(ccc) \rightarrow \Omega^- + 3\mu^+ + 3\nu_\mu \qquad (16)$$

The mass distribution of the same-sign trimuon is rather easily estimated from the muon momentum spectra in the individual decays. A rough calculation gives the distribution sketched in Fig. 1.

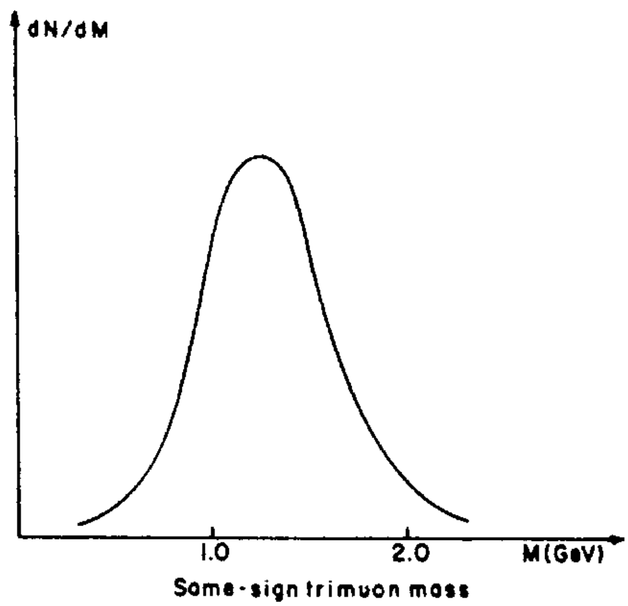

Fig. 1

Mass of same sign trimuons from triple semimuonic decay of the ccc.

The combination of low-mass, same-sign trimuon and missing hadronic energy makes a potentially powerful signature for a trigger. It then would have to be supplemented by good vertex information.

PRODUCTION DYNAMICS

The status of our understanding of charm production by hadrons is rather abysmal. We resort here to some (optimistic?) guesswork on production cross-sections based on scanty data and counting rules.

It seems reasonably clear that the ccc (plus $\bar{c}\bar{c}\bar{c}$) system was, just before birth, a system of <u>gluons</u>. Thus valence quarks probably are quite irrelevant, except that the more initial momentum carried by quarks, the less initial gluon momentum is available for the (ccc) production. This implies the importance of fluctuations in total quark momentum in getting the best yield. Hence there may conceivably be, for (ccc) production, an advantage in use of incident <u>mesons</u>. In particular, the use of π^- to make a forward $(ccc)^{++}$ may well minimize unwanted backgrounds of irrelevant baryons and/or strangeness.

With this in mind, Table IV exhibits some guesses of production cross-sections of leading baryons ($x > 0.4$) by π, K, N, and Y. Some of the interesting inputs from experiment are the A, T production[3] by Σ^- and the Λ_c production[7] by 40 GeV neutrons at IHEP. Ignored is any potentially contrary evidence[8] for a lack of large forward Λ_c production at SPS/Fermilab energies.

<u>Table IV</u>

Some guesses for production cross-sections of leading baryons containing heavy quarks ($\sqrt{s}$ = 40 GeV; $x > 0.4$) by incident hadrons. The substitution $c \rightarrow b$ may cost a factor ~ 100 in cross-section at this energy.

	n,p incident	π incident	Σ^- incident	K^- incident
Σ^-(dds)	500 μb	50 μb	--	500 μb
Ξ^-(dss)	25 μb	5 μb	--	50 μb
Ω^-(sss)	0.5 μb	0.5 μb	--	5 μb
Λ_c(cud)	50 μb	5 μb	--	--
A^c(cus)	2.5 μb	500 nb	50 μb	5 μb
T (css)	100 nb	50 nb	2 μb	500 nb
(ccd)	10 nb	20 nb	--	--
(ccs)	500 pb	500 pb	10 nb	5 nb
(ccc)	3 pb	10 pb	3 pb	10 pb

The recent measurements[9] of Ω^- production by K_L are also interesting. The data exhibits a forward peaking, perhaps a little more than one might expect from phase-space alone. Additional normalizations come from data[10] on Ξ and Λ production by π and K. Nothing should be regarded as better than a factor 3-10 in these estimates.

The longitudinal-momentum distributions are, in general, in reasonable agreement with counting rules.[11] The rule is, for $a + N \to c + \ldots$,

$$E \frac{dN}{d^3p} \sim (1-x)^F \tag{17}$$

with F equal to the net number of quarks in the $a\bar{c}$ system. Thus for $\pi + N \to (ccc) + \ldots$, the power F is 5, while for an incident baryon it is 6. This is indicative of some favoritism for mesons.

The transverse-momentum of the produced (ccc) should be rather large. Existing data on hyperon production suggests a mean p_T in the neighborhood of $(1.2 \pm .2)$ GeV.

Details of actual production mechanisms are also important. Is peturbative $g+g \to Q+\bar{Q}$ the way to think about this? Is "flavor excitation" with an $A^{2/3}$ dependence and diffractive-like morphology relevant? Where in phase-space is the associated anti-system and what is it? The data on $K_L \to \Omega^-$ would be especially interesting if correlation information could be extracted.

Finally, there is the matter of cross-section normalization. The guess for forward ($x > 0.4$) ccc production at Fermilab energies is $\sim 3\times10^{-35}$ cm^2. To gain some perspective, this corresponds to 10 produced (ccc) per MHz of interacting primaries per day at the Fermilab Tevatron, or 1 (ccc) per 2 billion interactions.

EXPERIMENTAL PROSPECTS

Our discussion has suggested two possible methods for finding the (ccc). The first uses the A and T as tags, with the detection technique generalized from the discovery experiments. The second uses the same-sign trimuons plus missing-energy as a trigger. In both cases, these tags must be used very efficiently to reduce the trigger rate and limit the size of the sample which must be analyzed. The final isolation of the signal must come from observation, via a powerful vertex detector, of the doubly charmed track and its decay products, which in turn are matched to the information in the downstream spectrometer. With an estimated cross-section of $3\times10^{-35}cm^2$ and a goal of, say, 30 reconstructed (ccc), we may then estimate how many interacting protons are required. In the first method, we assume 50% of all (ccc) cascade to A and/or T, and that the branching ratios of A to $\Lambda K^- \pi^+\pi^+$ and T to $\Xi^0 K^- \pi^+\pi^+$ are each of order 10%. With 50% acceptance plus reconstruction efficiency, and an efficiency for detection of the doubly charged track at the vertex to be 30%; this gives an overall effective cross-section $\sim 2 \times 10^{-37}cm^2$.

Upon demanding 30 reconstructed events, this gives an overall requirement of $30 \times (5 \times 10^{-26})/(2 \times 10^{-37}) \sim 10^{13}$ interacting protons per experiment (i.e., 5-10 MHz interaction rate at the target). If we assume no more than $10^{7\pm1}$ vertex events can be analyzed, this implies a rejection factor at the trigger of $\sim 10^{6\pm1}$. This must presumably be accomplished by a fast on-line trigger processor, which, in addition to searching for Λ and K^- from the spectrometer data, must demand an A and/or T candidate via a rough reconstruction of the mass. In addition, vertex activity (multiplicity rise) and overall multiplicity probably needs to be added into the triggering requirement. It would seem that an electronic vertex detector (e.g., Si microstrip, CCD) would be required rather than a visual one (e.g., streamer chamber) in this approach.

The trilepton trigger requires more protons/experiment but less demands on the spectrometer. Assuming a 17% muonic branching ratio per stage and an overall trigger efficiency $\sim$ 50%, along with the same 30% vertex efficiency and demand of 30 observed (ccc) events in the experiment as before, gives a requirement of 5×10^{14} interacting primaries per experiment. This implies an interaction rate in the target of 100-200 MHz, formidable indeed, along with a rejection factor for the trigger of $10^{8\pm1}$. The generic layout of such an experiment would be a compact vertex detector plus nearby tracking chambers immediately followed by a compact, accurate calorimeter (U/liquid argon?) and a downstream muon spectrometer. The signature would be a same-sign trimuon system of low mass (rejection $\geq (10^2)^3$??) along with missing energy in the calorimeter. This missing energy is considerable, more than 25% of the initial energy:

$$\Delta E \approx \left(1 - \frac{M\Omega}{M_{ccc}}\right) \; x_F^{(ccc)} \; E_{beam} \geq \frac{E_{beam}}{4} \tag{18}$$

Despite inevitable correlation of a ΔE trigger with the trimuon trigger, this should help in providing additional rejection (factor 10?). And again the multiplicity increase and/or evidence of a doubly charged track in the vertex detector may conceivably be implementable into the trigger.

Indeed, a very attractive option would be a stand-alone vertex device which could itself trigger on a doubly charged (4 x minimum ionizing) candidate track which is seen to decay predominantly into only 2 charged prongs. This requirement might be supplemented by evidence of the 3 other secondary vertices in the event. This would in turn demand on-line reconstruction of the event, something which nowadays seems quite thinkable. This general method has the great advantage of not having to pay the price of small decay branching ratios (and large spectrometers!). A detection efficiency of 30% and a demand of 30 produced (ccc) requires ~ 3×10^{11} interacting protons per experiment, i.e., an interaction rate of 100 kHz. The rejection at the trigger level most likely would have to be considerable ($\gtrsim 10^{4\pm1}$??) in order to handle the data load, and this may be hard to achieve. My guess for the resolution requirement is (ideally) a few microns(!!) in the transverse direction and perhaps 200 microns in the longitudinal. Coverage of a region, say ± 250 μ transverse to the beam particle and $\lesssim 2$ cm downstream of the vertex would suffice; this leads to the number of "pixels" (in projection) which need to be recorded to be ~ (100-200) x 100 (transverse x longitudinal), already a very thinkable number. Possible detectors which come to mind are silicon microstrips, CCD's, and scintillating fibers.

What about backgrounds within the sample? I will, out of naivete and ignorance both, not try to guess the limiting "mundane" backgrounds. However, there are quite a few "backgrounds" which are not without their own intrinsic interest.

We have guessed that for each (ccc) produced there are ~ 50,000 A's and T's. Hence in the first method a sample in excess of 10^5 reconstructed A's, or ~ 10^4 T's is required. (This is a factor 10^3-10^4 improvement over the existing sample sizes). These A's and T's are mainly directly produced, and will not exhibit the cascade via a doubly charged parent. However, the (ccu) may be expected to cascade through the A, and there are ~ 100 to 1000 (ccu)'s produced per (ccc). Detailed vertex information on the double cascade to the A seems to be required to remove such a background. Use of the T final state is an alternative which may be a more attractive one; it should not be fed much by the (ccu), but most likely is strongly fed from (ccc).

Less in the nature of backgrounds are "contaminations" of the A and T samples by other cascade mechanisms. For each (ccc) which cascades to T, we may expect ~ 20 (ccs) and perhaps a comparable number of (bss). For each (ccc) which cascades to A, we might expect, in addition to the serious background of ~ 100-1000 (ccu), a similar number of (bus) baryons and perhaps even a few (bcu) baryons which also cascade via the infamous (ccu) background. Some of these "contaminations" might provide diversions and amusement while the serious search for the (ccc) proceeds.

If one opts for semileptonic decay cascade chains as a preferred triggering mechanism, there are various ways of obtaining "significant" multilepton signatures. By a "significant" lepton, we mean one originating in a heavy quark decay. (In presence of electromagnetic backgrounds, "prompt" seems a misnomer.) There will be, of course, serious additional sources from the electromagnetically produced dileptons and muons from π and K decay. Without worrying about kinematic distinctions (important!), which require realistic simulations, we may catalogue a variety of candidate multilepton sources which compete favorably with the same-sign trimuon signature for the (ccc). These mechanisms are in fact already familiar in the context of multilepton signatures at the CERN $Sp\bar{p}S$ collider. For simplicity in estimation, we shall in what follows assume a 17% muonic branching ratio for either c or b, irrespective of the specie of parent hadron.

We start with tetraleptons. If we do not distinguish branching ratios as a function of the parent hadron species, then there are basically two sources of "significant" $\mu^+\mu^+\mu^-\mu^-$ tetraleptons. One is bottom pair production (σ ~ 10^{-31} cm^2?) with semileptonic decays of each c or $\bar{c}$ quark. Folding in the factor $(17\%)^4$ still gives σB^4 ~ 10^{-34} cm^2 for $b\bar{b}$ and σB^4 ~ 2×10^{-35} for $(cc\bar{c}\bar{c})$, as compared with the σB^3 ~ 2×10^{-38} for the (ccc). However, the mass distribution will be much broader for these "background" processes. Furthermore, all of these mechanisms are swamped by electromagnetic tetralepton production, which we might estimate as ~ $3 \times 10^{-33\pm1}$ cm^2. On the face of it, none of these mechanisms are damaging either in terms of trigger rate or signature. Indeed, none provides a same-sign trilepton - although it only costs a factor ~ 3×10^{-3} (??) to pick up a stray lepton of either sign from π decay while much (~ 2×10^{-2}) of this loss is regained by not requiring any "opposite sign" lepton in association with the desired trilepton.

If one is willing to settle for a (ccu) search via a same-sign dilepton trigger (plus vertex detectors, of course), then σB^2 for the signal is $\sim 5 \times 10^{-35} cm^2$, with background from π and K decay ($\sigma \sim 10^{-30} - 10^{-31} cm^2$?) up a factor $\sim 10^4$ and with the other "significant" backgrounds ($\sigma B^2 \sim 5 \times 10^{-33}$ for $b\bar{b}$; $\sigma B^2 \approx 10^{-33}$ for $cc\bar{c}\bar{c}$??) considerably larger than the signal. Again the mass and momentum distributions plus vertex information must be used to cull out the desired signal.

As for the stand-alone vertex detector, again the (ccu) background ($\gtrsim 10^3$) is formidable, requiring either a downstream system, a lucky cascade of (ccc) through (ccu) within the vertex detector itself, or evidence of a triple cascade.

This discussion is very superficial. But it should again indicate that there are in principle interesting diversions and amusements within a direct multilepton sample, which may help ease the inevitable frustrations bound to occur enroute to the (ccc).

CONCLUSIONS

Finding the (ccc) baryon would seem a worthwhile goal, were it not so obviously painfully difficult. Study of the baryonic analogue of charmonium might yield sharp tests for QCD. But irrespective of that, there are consolation prizes along the way, most notably the (ccu). Just the observation of a doubly charged, four-times-minimum ionizing particle with lifetime $\sim 10^{-12}$ to 10^{-13} sec would be great to see. And the plethora of cascade mechanisms present in the background processes, if resolvable, would surely lead to a new dimension in baryon spectroscopy.

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